

**GEOLOGICAL SURVEY OF CANADA  
COMMISSION GÉOLOGIQUE DU CANADA**

**Open File 813**

**PHOSPHATES OF BAJA CALIFORNIA  
SUR-POTENTIAL SOURCE FOR CANADA'S  
FERTILIZER INDUSTRY**

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**1981**

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## INTRODUCTION

A field trip in southern Baja California, Mexico, in February, 1981, saw an international group of geologists gathered to study Miocene and younger phosphorites of the region. The meeting was one of several that have been carried out by "Project 156 - Phosphorites" of the International Geological Correlation Program (IGCP), a joint program of the International Union of Geological Sciences (IUGS) and Unesco (Fig. 1). The meeting, a 'field work-shop and seminar', was held in La Paz, B.C.S.; the discussions and field visits were organized by geologists of 'Rofomex' (Roca Fosforica Mexicana, S.A. de C.V.) who, we can presume, hoped that some good would arise from the assembling of many of the world's leading phosphate researchers for field study and discussion.

These notes contain some observations made during the field trip; the basic geological descriptions of the phosphatic sections, however, are abstracted from reports by F.J. Escandón (Director) of Rofomex and J.O. Rivera of Consejo de Recursos Minerales, Mexico, and from a preprint of a paper by G.P. Salas (1978) for the American Institute of Mining Engineers. My debt to these people, and to other guides of the field trip, is gratefully acknowledged.

Estimates of shipping costs, noted in Table 1 of this paper, derive from discussion with Mr. G. Barry of Canmet, Ottawa. The rail costs, Vancouver to Calgary, are quotes (by telephone) from the freight departments of Canadian Pacific and Canadian National railways.

### Phosphates, present and future, in Mexico

Only some 20 000 to 35 000 T of phosphate rock are produced annually in Mexico (British Sulphur Corporation, 1971; figures to 1969); most of this (low-fluorine) rock is exported to U.S. for use in animal feeds. Some rock is applied directly to fields. The Mexican phosphoric acid and fertilizer industry, which now uses some 1 700 000 T of

# INTERNATIONAL GEOLOGICAL CORRELATION PROGRAM

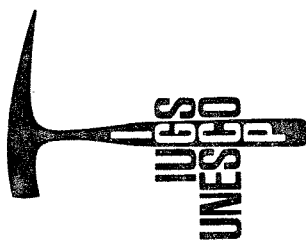
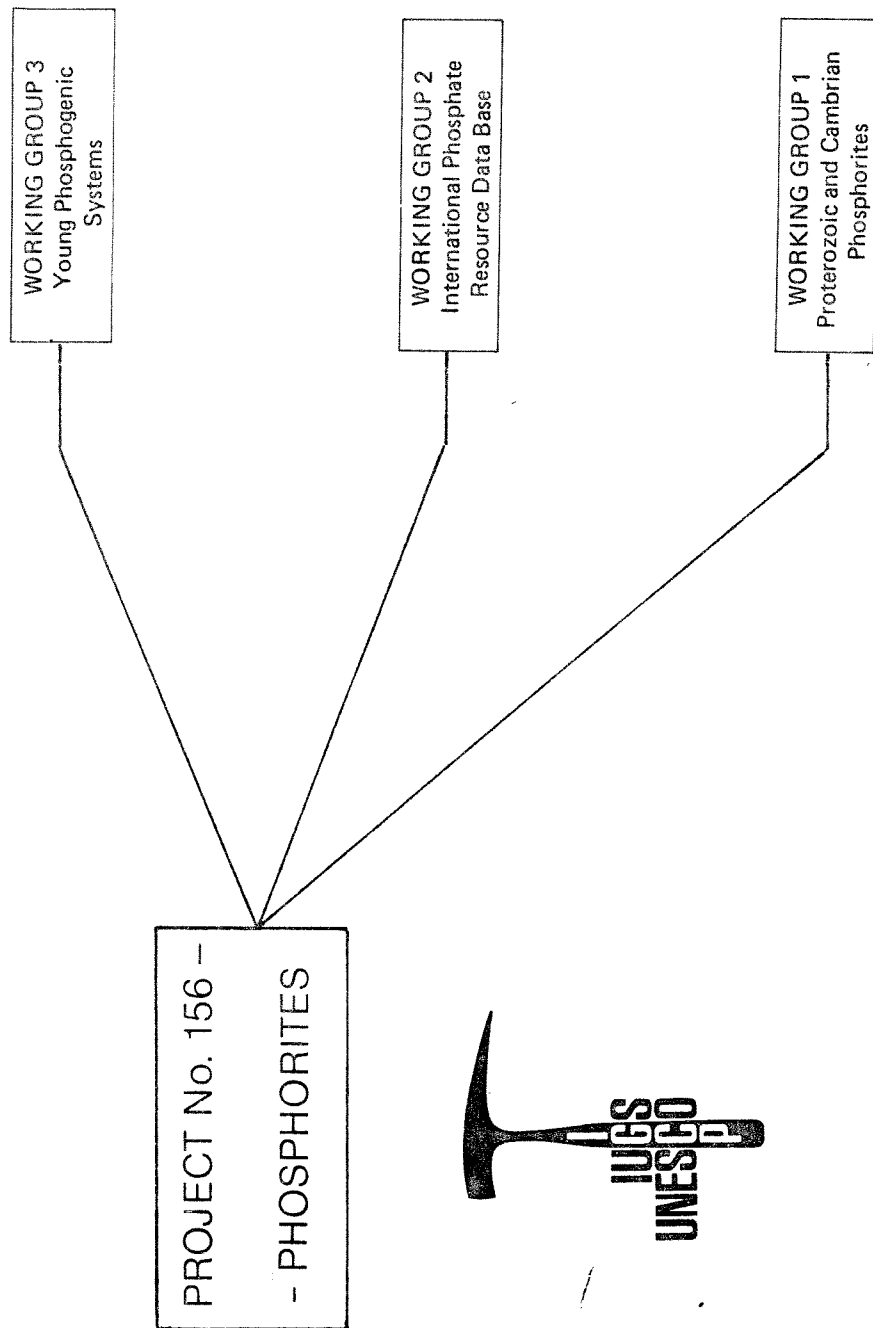


Figure 1. Project 156 of the International Geological Correlation Program.

Source of Phosphate Rock	Cost at Source	Shipping Cost	Port Transfer	Rail Cost per T. CN CP	Total Cost, Calgary
Baja California	\$30 ?	marine: \$15-20 ?	\$3	<div> <div> mixed train, &gt;95% of car cap. </div> <div> \$24.20 </div> </div> <hr/> <div> <div>140,000 lb. covered hopper cars</div> <div>30.40</div> </div>	\$73/T ++

Western  
States

Florida

Table 1. Table of costs for alternative sources of phosphate rock for shipment to Calgary.

phosphate rock annually (Killin, 1976; figure for 1974), is almost totally dependent upon imported rock. When the price of phosphate on the world market escalated sharply in 1974-75 (e.g. from \$15/T to \$60/T in Morocco), Mexico began intensive exploration for phosphates in order to expand domestic supplies.

The existing phosphate mines in Mexico are in Upper Jurassic and Cretaceous beds. Some guano has been mined. These phosphate districts lie on the eastern side of Mexico, close to the Gulf of Mexico (see Fig. 2; locality 1).

Offshore and coastal deposits in Baja California have been known for some time. Several Mexican-American companies have examined them, and processes have been developed to upgrade the rock from 3 to 31 per cent  $P_2O_5$ . In the past decade, Mexican companies have carried out aerial radiometric surveys which have led to discovery of several previously unknown deposits in southern Baja California (Fig. 2; localities 2, 3).

Only about 20 per cent of the land of Mexico is suited to agriculture (Salas, 1978). Planners reason that greater use must be made of fertilizers in order to keep pace with the demand for food by the growing population (now about 70 million).

Fertilizer demand is increasing markedly (imports: 1968, 300 000 T; 1974, 1 700 000 T), perhaps because farming in Mexico is tending more toward organized food production and away from peasant, or subsistence farming. The phosphate rock is imported from Florida, Morocco, and Spain. Mexico hopes soon to reduce its dependence upon foreign supplies and indeed expects, by the mid- 1980's to be able to export phosphate rock on a significant scale.

The possibility, or indeed probability, that phosphate rock will become available for purchase on the Pacific Coast of North America should be considered seriously by Canadians. Some factors in this potential source of phosphate for the Canadian fertilizer industry are discussed later in this paper.

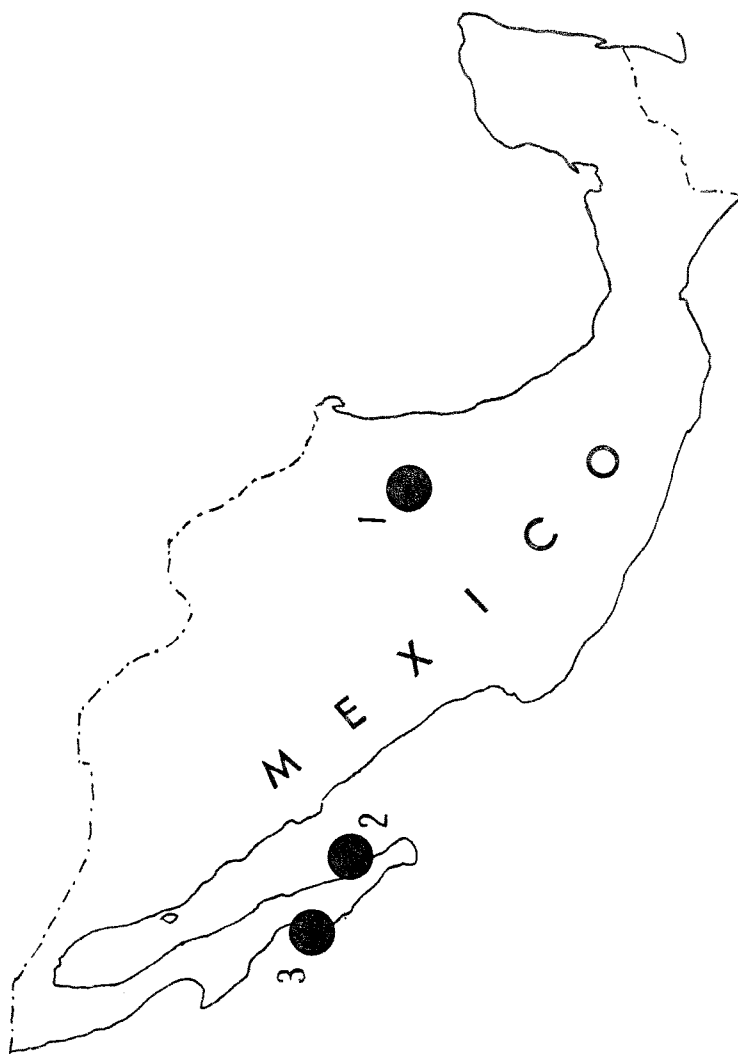


Figure 2. Principle phosphate districts of Mexico (Numbered localities are referred to in the text).

#### Sites under development, BCS

Mexico's hope for substantial production of phosphates for domestic use and for export is expressed in the development of two mines: a) at San Juan de la Costa, some 80 km north of La Paz, where Monterrey Formation (Miocene) has been stripped, an adit prepared, and a plant and townsite built (Fig. 2, locality 2); and b) the Santo Domingo project, 220 km northwest of La Paz, where Pleistocene - Recent beach sands adjacent to Bahia de Magdalena have been tested and an ore dressing technique developed (locality 3).

The developing mines will be described in more detail after a review of the geology of phosphatic units.

#### Geomorphology, Baja California Sur

Baja California Sur is the southern half of a peninsula 1700 km long and 50 to 100 km wide. The Pacific Ocean washes the west side of the peninsula, and the Gulf of California (Golfo de Cortés to the Mexicans) the east side. The peninsula is mixed mountains and plains: Mesozoic sedimentary and metamorphic rocks and batholiths stand above flanking lowlands of nearly flat-lying Cretaceous and younger sedimentary and volcanic rocks. Some 1000 m of Cretaceous flat-lying conglomerate, sandstone, and shale underlie western Baja California, and these beds are covered by variable thicknesses of Tertiary and Quaternary sandstone, siltstone, tuffs, flows and unconsolidated debris (Fig. 3).

Baja California is evidently a continental slice that became detached from mainland Mexico some time in the last 50 m.y.; the detachment took place after middle Tertiary time as a result of complex movements at the north end of the East Pacific Rise (de Cserna, 1975).

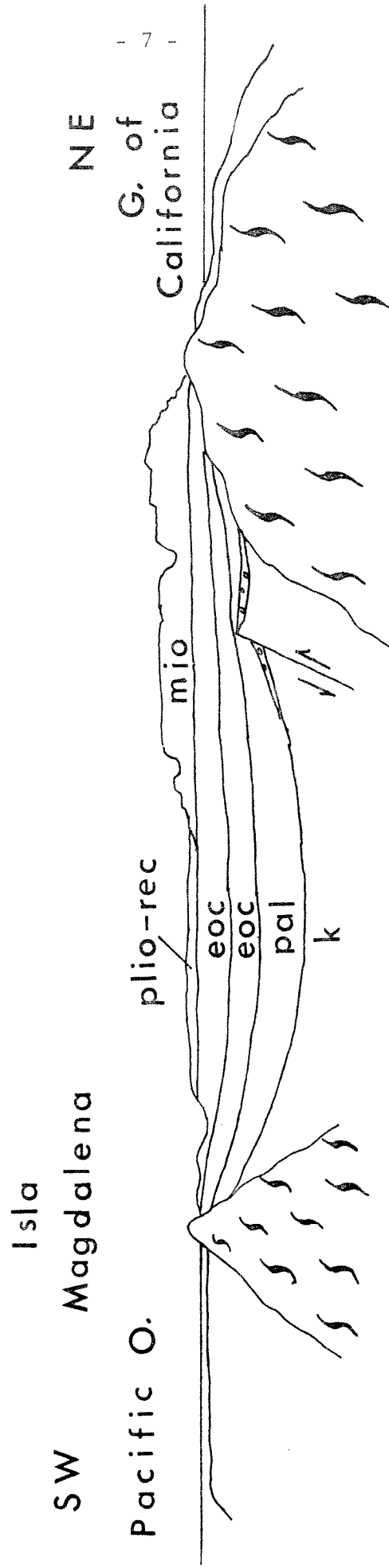


Figure 3. A diagrammatic cross-section of Baja California Sur (After Salas, 1978, Fig. 12)

## GEOLOGY OF THE PHOSPHATE BEDS

The phosphorites are contained in a basin of slightly-disturbed sedimentary and volcanic rocks that range in age from Paleocene-Eocene to Pliocene-Pleistocene. The maximum total thickness of the Tertiary beds is about 4600 m. Phosphate pellets occur at several levels; the phosphate probably has been extensively reworked from one unit to another (see Fig. 4).

### Tepetate Formation

Paleocene-Eocene; up to 1300 m of coarsely stratified yellow to brown, fine-grained siltstone and sandstone; no phosphatic facies known. The sandstone is crossbedded in places; beds examined were of uniform grain size, and nearly massive (disturbed? --- flowed?). Large (3 mm) Nummulites are present in sub-horizontal bands and are also oriented 'in swirls', the flake-shaped fossils parallel but forming sweeping curves.

The foraminiferal assemblage has been taken as characteristic of 'upper to middle slope deposits'.

### Monterrey Formation

Lower and Middle Miocene; overlies Tepetate Formation with an erosional and very slight angular unconformity. The unconformity is marked by a thin basal bed of volcanic conglomerate with a sandy matrix that contains phosphate and abundant fossils, especially sharks teeth. Conditions favouring phosphate deposition had arrived in Baja California.

The Monterrey Formation comprises yellow to brown, well-bedded siltstones, 'cherts', other siliceous and tuffaceous fine-grained sedimentary rocks, and sandstones. Phosphate oolites or pellets have been recognized throughout the section; shales in the section assay up to 1.5 per cent  $P_2O_5$  and sandstones generally between 8 and 27 per cent.

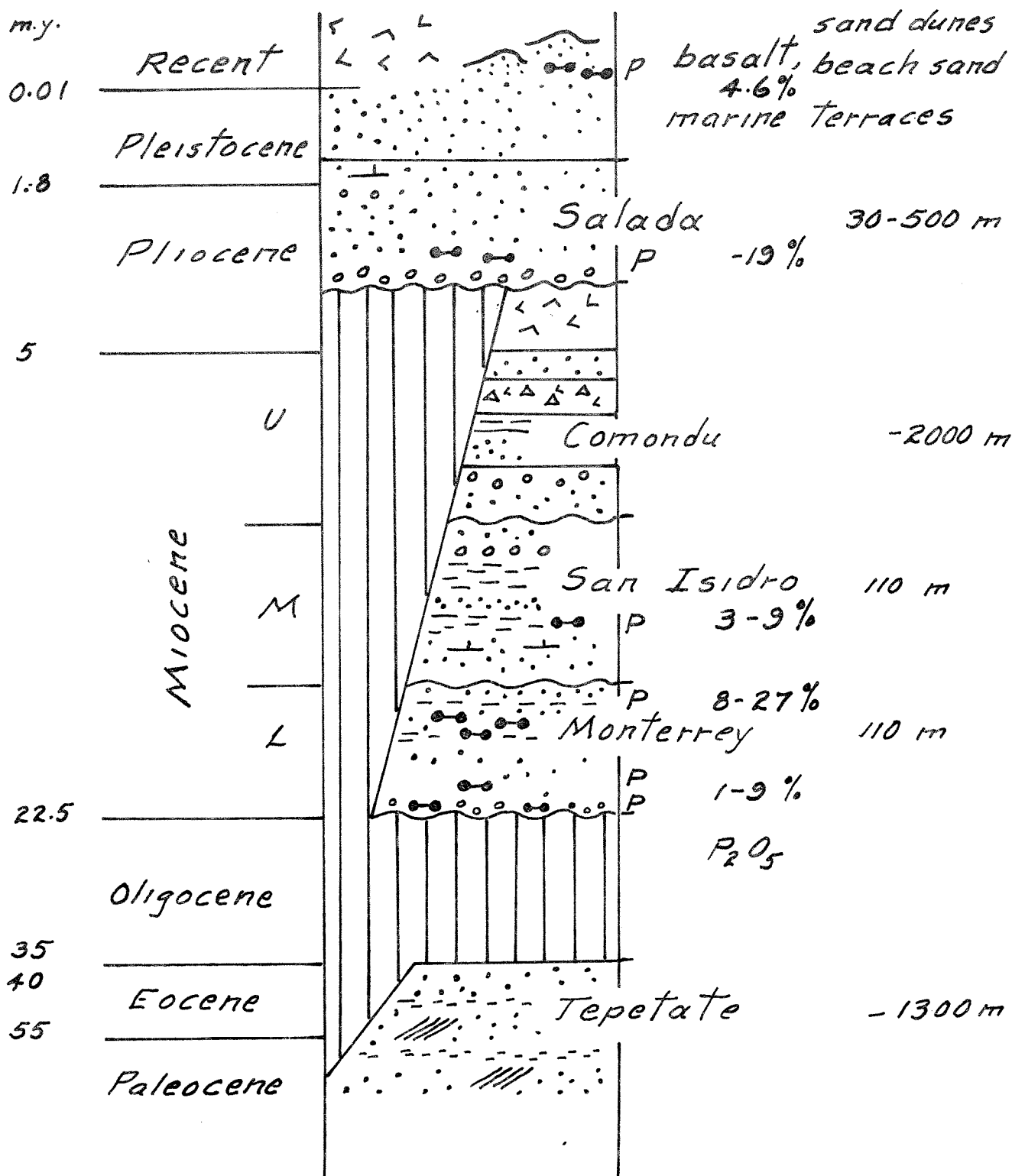


Figure 4. Paleocene-Recent stratigraphic column, Baja California Sur.

The unit has been divided into two members: the lower one slightly phosphatic (1-9%), the upper one more so and of economic interest (8-27%). The lower member, 70 m, consists of fine- to medium-grained sandstones with clayey sandstones, shale, and diatomite beds. The phosphate occurs as 'oolites', mainly in thin beds of siltstone. The upper member, 40 m, comprises thin beds of shale and sandstone with some thicker sandstone beds. The phosphate occurs in the sandstones. Thin beds of diatomite are present, the shales are 'silicified', and some beds are calcareous.

Examined were beds >1 m of phosphatic sandstone; these are well indurated, with conspicuous bone fragments and shark teeth. The phosphate occurs as pale brown-yellow pellets.

The sedimentology of the phosphatic sandstone beds received a great deal of attention and discussion. Two schools of thought prevailed: a) the beds are thoroughly burrowed (bioturbated); and b) the beds are a form of turbidite. The beds, in fact, seem nearly massive, graded, with rip-up flakes at the base. Some very large, siliceous clasts (→20 cm) occur higher in the beds. The bottom surface is irregular and abundantly burrowed, the burrows up to 6 cm diameter. The largest burrows are horizontal, but some big ones are vertical and descend 5 or 6 cm into the underlying fissile shale bed. No load or flute features were seen.

One large clast appeared to be 'drifting' into two pieces, the coarse sandstone wedging it apart.

Thinner beds that are coarse-grained also are heavily trail-marked and cut by 'tubes' or burrows.

A member of the party insisted that bioturbation was adequate to explain the features, but some clasts seem simply too large - up to about 40 cm!

The Monterrey Formation varies laterally; for example, the proportion of sandstone and the average particle size increase from west to east, toward the San Juan de la Costa site.

#### San Isidro Formation

Middle Miocene; up to 680 m thick; overlies the Monterrey Formation with an erosional and angular unconformity. The phosphate content varies from 3 to 9 per cent, and locally is as rich as 24 per cent.

The San Isidro Formation has been divided, in the area examined into: a lower unit, 0 to 35 m thick, of thin bedded shales, fine-grained quartz sandstone, and fossiliferous limestone; and an upper unit, 80 m thick, of thin- to medium-bedded tuffaceous sandstones with beds of bentonitic clay. The upper unit is conglomeratic in places.

The San Isidro Formation was assigned an Early Miocene age by Minch and Leslie (1979) from its underlying relationship with 22 m.y. tuff beds on Cerro Colorado.

#### Comondú Formation

Upper Miocene to Lower Pliocene; up to 2000 m thick; unconformably overlies the San Isidro Formation. The unit is composed of medium to thickly bedded tuffaceous sandstones, coarse, poorly sorted volcanic conglomerates and agglomerates, and lavas. No phosphate has been observed in these sediments.

The Comondú Formation is thick and widespread and dominates much of the intermontane terrain of southern Baja California, with its green- and red-weathering volcanoclastic beds. Pink-weathering breccia from this unit is quarried and much used for retaining walls and buildings, to which it imparts a beautiful pastel pink colour. The stone is extremely porous and light, and is easily cut - an ideal building material for this arid climate.

Radiometric ages for this unit are:

14 m.y.

18 m.y.            - pink breccia

19-24 m.y.        - andesite breccia

The volcanic source appears to have been to the east, judging from crossbeds and mud flows in the Comondú Formation. The volcanic rocks north of La Paz seem to match breccias at Mazatlan, about 2° south. This movement would conform with the evidence from the overall geological and tectonic framework, which indicates opening of the Gulf of California after middle Tertiary time and northwestward drift of the peninsula. The movements occurred along a southern continuation of the San Andreas Fault and the northern end of the East Pacific Rise (de Cserna, 1975). [The youngest basalts in the Gulf are dated at 4 to 5 m.y.].

#### Salada Formation

Pliocene-Pleistocene; 30 to 500 m thick; rests on an erosional and angular unconformity that cuts through the San Isidro and the Monterrey Formations and part of the Tepetate Formation. This unit is weakly consolidated, rudely bedded sandstone. Phosphate occurs as a brown coating on a distinctive basal conglomerate and as pellets in the lower sand beds of the unit.

The phosphate values in the sandstones are 'cyclic': more- and less- rich beds alternating, and with the phosphate values decreasing upward from about 10 per cent  $P_2O_5$ . Phosphate assays as high as 19 per cent are recorded. The phosphatic sands are uniform and fine-grained, but are poorly sorted in that they are rich in 'fines'.

#### Pleistocene and Recent deposits

A widespread cover of volcanic debris, gravel, cobbles, and blocks rests on an eroded surface of the Tertiary and older sediments; this cover is characteristic of

the western flanks of the sierras that form the 'backbone' of the peninsula and of the low hills and mesas to the west. Smaller amounts of fluvial, lacustrine, and aeolian deposits also were deposited in Quaternary time. Recent beach sands and windblown sand lie along the coasts; phosphate pellets occur in these beds and a zone some 70 km by 20 km near Santo Domingo is of economic interest. The phosphate pellets vary considerably in colour - from yellow to dark brown - and it seems clear that they were derived from the older formations.

The proposed orebody is mainly fine sand with rounded grains; minor magnetite, ferromagnesian minerals, rutile, sphene, etc. are present. Phosphate grades average about 4.5 per cent  $P_2O_5$ . The sand will be mined by suction dredge.

Test pits had been dug by bulldozer and by hand, and in these can be seen pale grey-white (unweathered, in the pit bottom), and brown sand. The brown sand, about 3 m thick, presumably is a weathering profile; root casts (sand calcified around the root, which now is gone) were observed to depths of 6 m. No buried weathered surfaces or soil profiles could be seen. The sand is uniformly sized; apatite pellets, dark minerals, and thin flakes of carbonate shell material all are evident.

A coquina bed was seen in a 2 m deep pit; this appeared to be a beach deposit, and is now overlain by dune sand.

The field group crossed the bahia to Isla de Magdalena by barge, then traversed the island, which is a longshore barrier bar some 1 to 3 km wide. The Pacific Ocean side, we discovered, is a graveyard of ships and old trucks.

In the swash zone, one can see abundant heavy minerals, including apatite. This sand is picked up by the oceanic winds and carried inland as dunes. The bedding in the dune sand is conspicuous, and the question arises: why are the aeolian sands inland so massive (structureless)? An explanation may be that the inland sand has been reworked during repeated submergence.

'Turkey clams', a species of pelecypod, were noted on the beach by Stan Riggs, who states that they are evidence of 'hard ground' offshore. The Tertiary formations are probably exposed as submarine outcrops, and the phosphate and sand material is recycled by waves and wind into the Recent deposits.

### ORIGIN OF THE PHOSPHATES

How did the Baja California phosphates come to be, and if we could understand their origin, would the knowledge help us find more phosphates?

#### Theory of origin: the prevailing opinion

There are several theories to explain sedimentary apatite, or phosphorite, and it is interesting to review the development of thought on this problem. It suffices here to say, however, that the picture must be something like this (Wang and McKelvey, 1976; Cook, 1976; Cook and McElhinny, 1979; Kolodny, 1979; Riggs, 1979; Burnett, 1980):

Phosphorites are related to the open ocean in that they evidently form on continental platforms and slopes adjacent to known 'oceanic upwellings', which are ascending currents that bring cold, relatively phosphate-rich deep water to the surface. However, most phosphorites form not in the open sea environment but in more protected localities where several important features may coincide:

a) where a depositional site can be enriched in phosphate ions through the intermediary of marine organisms - e.g. plankton.

b) where more or less restriction of circulation may result in reduced oxygen levels (thanks to the abundant organic matter); the most favourable sites for phosphate deposition appear to be at the margins of oxygen-minimum zones - particularly the upper margin.

c) where sedimentation (introduction of terrigenous material) is limited; that is, accumulation is slow or intermittent, this due to one or both of prolonged tectonic stability and arid climate.

d) the development of large and rich phosphate deposits - i.e. of economic interest - is favoured by periodic agitation of the newly deposited sediments and by reworking of earlier beds and resulting 'condensation' of the stratigraphic column.

e) phosphates occur in rocks of almost all ages but certain times evidently were favoured, perhaps due to a combination of widespread inundation of continental areas to form shallow seas, a general warming of the oceans, diversified and abundant development of plankton, and a low marine oxygen level to favour widespread deposition and preservation of organic material.

How does this 'conventional wisdom' fit with the situation at Baja California?

Clearly, Baja California was in a favourable geographic position for phosphate deposition throughout Tertiary time: well within the 40°S to 40°N latitude zone established (Sheldon, 1964; Cook and McElhinny, 1979) as favouring deposition of phosphorite; and lying on a coast impinged upon by wind-driven ascending and longshore ocean currents. Other factors allowing phosphate deposition also occurred: favourable paleogeography and a phosphogenic episode.

Paleogeography: the early Tertiary Baja California evidently was a belt of narrow seas or bays with highlands on the east and discontinuous barriers on the west. The bays or seas were connected with the Pacific Ocean, but were shallow and relatively restricted in circulation. Both the highlands and the barriers consisted of resistant Mesozoic rocks that probably were raised partly or entirely through block-faulting (Salas, 1978).

The sedimentary conditions were those of irregular, shallow basins connected by shoal water, and with numerous islands and shoals. The SE-flowing, cold California Current passed along the outer barriers, and possible prevailing SW-blowing winds aided in creating ascending currents that spilled into the protected, warmer bays and seas. The paleogeographic and sedimentary conditions

in Baja California probably were, in many ways, similar to those postulated for the Florida peninsula in Miocene time: a persistent arch (the Ocala Arch) created shoal water on a shallow platform onto which deep ocean water was moved by wind-generated currents (Freas, 1976; Riggs, 1979) (see Fig. 5).

The peninsular area, Baja California, was protected from floods of continental sediments from the mainland to the east by a proto- Gulf of California or by a topographic low along the fault zone. The autogenous phosphorite and the relatively small amounts of sediment in the shallow Paleocene-Miocene seas were subjected to protracted reworking and sorting. Transgression and regression occurred repeatedly, probably due to intermittent faulting along the gulf rift; the peninsula evidently was emergent during all of the Oligocene.

The Monterrey Formation comprises siltstones, argillites and other fine-grained rocks deposited under quiet-water conditions; phosphorite and diatomite indicate abundant organic development; scattered gypsum layers in certain areas indicate restricted circulation. The extensive bottom burrowing is characteristic of shallow water. All these features would be compatible with restricted small seas with shoals, and a warm, arid climate. The 'turbidite-like beds' could be due to intermittent transport of unconsolidated sediment from shallower to deeper bottom areas, movement perhaps triggered by occasional tremors due to activity along the nearby proto-gulf.

#### DEVELOPING PHOSPHATE MINES

Numerous sites have been tested; two have been chosen for initial production on account of such factors as grade, proximity to shore, mining conditions, etc. Phosphate beds of the Monterrey Formation at San Juan de la Costa are now developed for production: the second mine site, called the Santo Domingo project, is at camp and equipment construction stage, with production planned for about 1983.

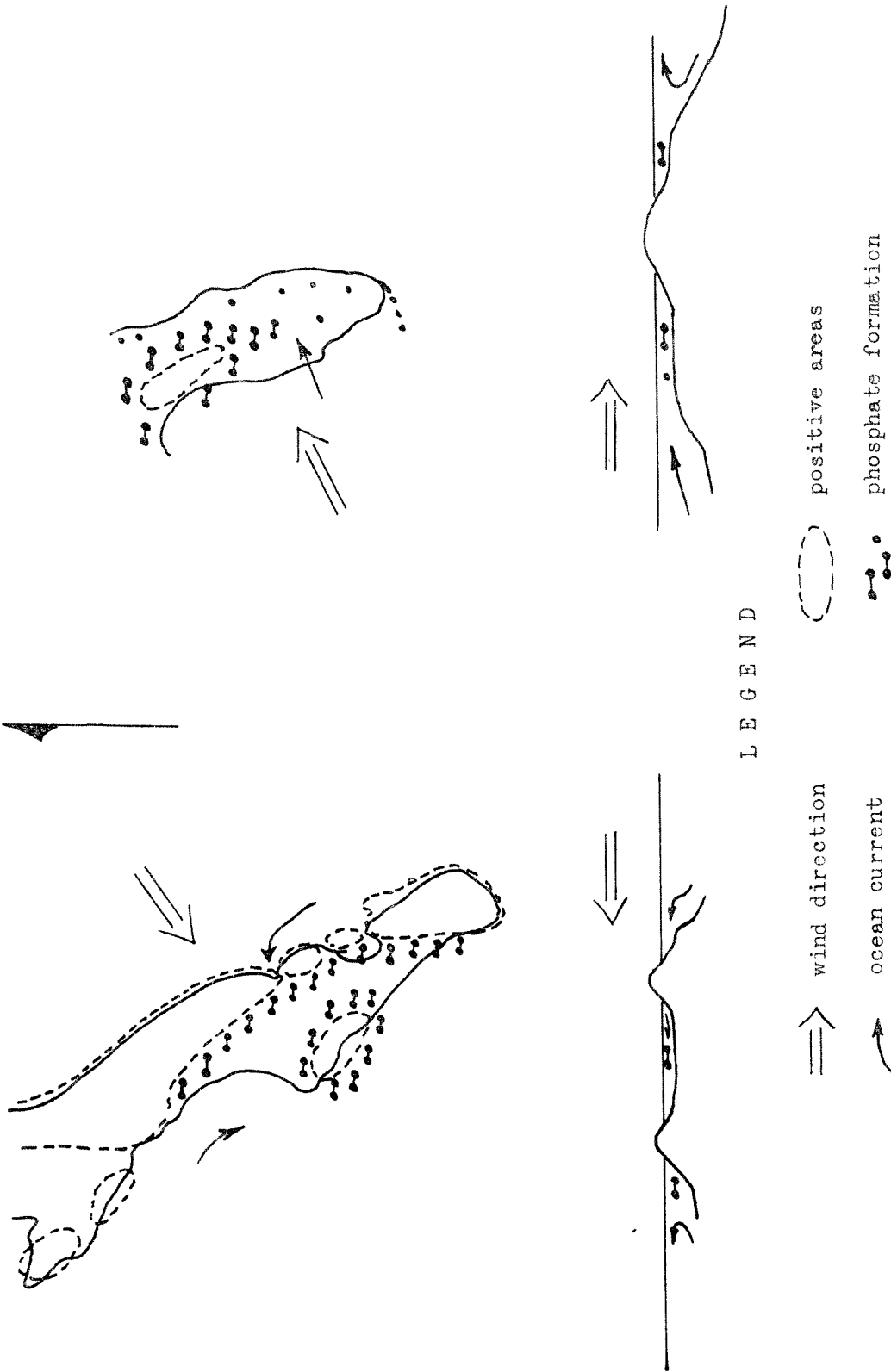


Figure 5. Diagrammatic representation of 'models' for sedimentation of (on left) Baja California Sur in Miocene time (after Salas, 1979) and (on right) Florida in Miocene time (after Freas, 1967).

San Juan de la Costa:

Here an extensive open pit has been developed, but now the intention is to go underground and mine one to three of the 8 potential ore beds. The beds range in thickness from 20 cm to 3 m, and the grades average about 20 per cent  $P_2O_5$ . Coal-cutter type mining machines will be used with room-and-pillar mining. The first stage of the beneficiation plant has been built, and the flotation plant is undergoing testing.

The ore is crushed, screened, classified, etc., ... then stored in concrete silos. The phosphate pellet product, after washing and dewatering, is stored outdoors on a huge, prepared flat area where, as it is moved seaward by bulldozer, it will sun-dry. The phosphate product finally will be moved by conveyor belt to transport ships.

Some workers for the mine and plant will live in a newly built camp nearby, but most will be bussed daily to and from La Paz - some 80 km by road.

Santo Domingo:

As noted - some 220 km from La Paz; the orebody has been tested by a grid of drill holes - 500 m centres ... the designated 'deposit' is about 70 by 20 km; the 'orebody' for the planned dredging operation is considered to be about 6000 hectares in area, or about 4 per cent of the 'deposit'. Hydraulic cutter suction dredges will mine sand to a maximum depth of 15 m below sea level, and the height of the face above sea level will average about 6 m. The dredges will feed a floating primary concentrator or beneficiation plant - the barge is now being built in Singapore. The primary concentrate (about 16-18% of the ore) will be piped to a land-based flotation plant where two products will be obtained: the most valued, phosphate concentrate at 32 per cent  $P_2O_5$ , and a heavy mineral concentrate - about 1 per cent of the ore - which will be 'stockpiled' in a separate part of the tailings pond so that it can be reclaimed in the future.

The mining plans are based on a computer-aided study of grades and tonnages; a cut-off grade of 3.0 per cent  $P_2O_5$  will result in an average grade of ore of 4.56 per cent and 4.29 per cent in two areas or blocks of the orebody. The mine will operate 24 hours a day, 330 days a year, and at the proposed 50 000 T/day mining rate, will operate for some 75 years.

The dredging operation will take place in an artificial pond separated from Bahia de Magdalena by a berm of undisturbed land. The beneficiation processes are 'closed circuit' and intended to avoid any problems of contamination of the bay, which is a well-known calving ground for grey whales.

#### A SOURCE OF PHOSPHATE ROCK FOR CANADA'S FERTILIZER INDUSTRY?

Mineral industry planners in Mexico hope to have a surplus of domestic phosphate rocks in the mid-1980s (see Anon., 1980) this rock will be produced at oceanside on the Pacific Coast and should be considered as a potential import to at least western Canada. A preliminary review of some of the cost factors follows:

Cost of phosphate rock at shipping point: the Mexican product comes from a region of relatively low-cost labour, and should have little trouble competing with either Florida or Western States rock on this basis. A value of \$30 per ton for Florida phosphate product was noted in a Rofomex account of the Santo Domingo project and this figure is used in Table 1.

Maritime shipping: a modest sea voyage - 4000 m - between Baja California Sur and Vancouver is about half the distance from Morocco to eastern Canada. Mexican rock should be competitive in this regard.

The demand for phosphate rock in western Canada is substantial: perhaps more than 1 000 000 tons per year. Movement of such tonnages should mean that ships of 20 000 to 40 000 tons cargo can be used, and an economic rate on the cost per ton can be achieved.

Port transfer and moorage costs: The Port of Vancouver is a major shipping terminus and transfer is not a problem. Ship loading equipment is being built in Mexico. A transfer cost of \$3 per ton is assumed.

Rail cost: quotes on Canadian National and Canadian Pacific rail charges, Vancouver to Calgary, are shown in Table 1. The rail distance from Vancouver to Calgary is about equal to that from the Western States phosphate field to Calgary, and except for the extra cost in climbing mountain grades, the rail charges should be similar.

An interesting alternative possibility would be tidewater processing of phosphate rock into fertilizer so that rail haulage of the rock could be avoided. Sulphur or sulphuric acid produced, say, by a smelter for non-ferrous metals on the British Columbia coast could be used as the reagent for treatment of phosphate rock.

Total cost of phosphate rock delivered in Calgary: many cost factors are unknown at this writing so that a cost comparison between Mexican and other sources cannot be carried out. It is possible, however, that the raw product and the shipping costs from Baja California by way of Vancouver could do better than match the costs of rock from Idaho-Wyoming or Florida; thus Mexico should be considered as a potential source of commercial phosphate rock. Mexican rock would appear the more favourable if U.S. mining, beneficiation, and rail costs were to rise, or if U.S. sources were restricted for any reason.

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